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ACOUSTO-OPTIC ISOLATOR (AOI)

Vincent J. Corcoran, et al

Martin Marietta Corporation

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Martin Marietta Corporation

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13. ABSTRACT

The effort has examined the isolation capabilities and overall operational efficiency of employing an acousto-optical frequency translator for the purposes of suppressing optical feedback generated instabilities in a laser MOPA chain. The operating principle is based on decoupling optical feedback from sustained laser oscillation by frequency translating the feedback such that it falls outside the gain bandwidths of any of the CO transition lines. Current progress has demonstrated successful optical feedback isolation, but, has experienced spurious acoustical and RF induced heating of the frequency translator which has limited its overall efficiency to approximately 10 percent.

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ACOUSTO-OPTIC ISOLATOR (AOI)

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PUBLICATION REVIEW

This technical report has been reviewed and is approved

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SUMMARY

Coherent CO_2 radars which have amplification stages following a CO_2 master oscillator have spurious feedback in the stages of amplification which tend to pull the frequency of the signal. The standard techniques for achieving isolation using nonreciprocal devices in the microwave or optical regions are impractical in the 10 micron region. An isolator concept has been developed at Martin Marietta using the acousto-optic isolator (AOI) concept. During this program, isolators are to be designed, fabricated and evaluated for their ability to inhibit optical feedback between amplifier stages in a master oscillator/power amplifier (MOPA) chain operating at 10.6 micrometers.

During the first half of this program a number of acousto-optic devices have been constructed and tested. Details of this work are reported in Section 3.1. The acousto-optic effect has been observed in each of the devices constructed and as a result of the tests modifications which should improve the devices are being incorporated.

A MOPA simulator has been assembled with a tunable, single frequency CO_2 laser and an amplifier in which large amounts of feedback can be simulated. Another tunable, single frequency CO_2 laser is used as a local oscillator to determine frequency effects in the simulator. The experimental setup is isolated from vibration to improve the signal stability. Details are given in Section 3.2.

Thermal effects have been observed on each of the acousto-optic devices. These effects have had deleterious effects which can be partially corrected by gas cooling. Simple vibration effects caused by simply tapping the acousto-optic device have been observed. The thermal and vibration effects have been discussed in Section 3.3.

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1.0 INTRODUCTION

This technical report is concerned with the progress for the first quarter of Contract F 30602-72-C-0475, Acousto-Optic Isolator (AOI).

The AOI is a concept developed by Martin Marietta to provide non-reciprocal isolation between stages in a master oscillator / power amplifier chain (MOPA) operating at 10.6 microns. The concept is based on the fact that optical or infrared radiation passing through an acousto-optic device is partially deflected and frequency shifted by the interaction with the acoustical wave. If the shifted wave is returned back through the acousto-optic device, the wave is again partially deflected and frequency shifted so that the wave has a total shift of twice the acoustical frequency. This effect which has been demonstrated can be used to prevent frequency pulling of a signal by spurious radiation which may be fed back in a MOPA chain.

It is the objective of this contract to design, fabricate and evaluate the performance of an acousto-optical high power isolator which will inhibit optical feed back between stages in a MOPA chain operating at 10.6 microns.

Included in the report are information on the construction and testing of acousto-optic devices for use at 10 microns, a description of the MOPA simulator, locking tests and preliminary results on vibration and thermal effects on the acousto-optic effect. Also included are an outline of the continued effort on this contract and suggestions for further work beyond the current contract which would lead to a further understanding of the AOI and make it a more useful device in conjunction with MOPA systems operating in the infrared region.

Future plans for the current contract include the demonstration of injection locking of the signal by amplifier feedback and the investigation of the isolation from locking that can be achieved by the acousto-optic device. This investigation will involve the variation of a number of parameters to determine the effect on isolation.

Because of the limited time on the contract, all of the observations cannot be investigated in detail. Thermal effects, bonding, transducer material, electrical design, etc., are areas that should be investigated in a future contract to bring the acousto-optic device to the next stage of development.

The achievement of the objectives of the program is expected to result in a new isolation technique that will have use in a number of applications at wavelengths longer than 2 microns.

2.0 THE ACOUSTO-OPTIC ISOLATOR CONCEPT

The concept of the acouto-optic isolator is illustrated in Figure 2.0-1. It is based on the fact that an acousto-optic modulator shifts the frequency of the deflected energy. Theoretically, a wave incident from the other direction will also be shifted in the same frequency direction so that radiation reflected back through the modulator will be shifted by twice the modulation frequency. In the case for a system in which the CO_2 oscillator operates on a transition whose fluorescent linewidth is approximately 50 MHz, the reflected signal can be shifted outside of the transition with a modulation frequency of less than 50 MHz. At 50 MHz, the acoustical attenuation is low and efficient coupling can be achieved easily.

In order to verify the fact that a double frequency shift occurs when the signal passes through the modulator twice an experiment described in Figure 2.0-2 was performed using a HeNe laser and a water cell as the modulator. Radiation from the laser was split by a dielectric coated beamsplitter. Half of the radiation was reflected to a mirror and reflected back through the beamsplitter to serve as the local oscillator. The other half was transmitted through the beam splitter and the modulator to a mirror which reflected the radiation back through the modulator. The doubly modulated beam was then reflected by the beamsplitter onto the detector (photomultiplier or avalanche photodiode). The electrical signal from the detector was preamplified and sent to a spectrum analyzer.

The results of the experiment are shown in Figure 2.0-3. Figure 2.0-3a shows the 26 MHz RFI from the modulator and the signal at 52 MHz which is optically detected. When the mirror that reflects the signal back through

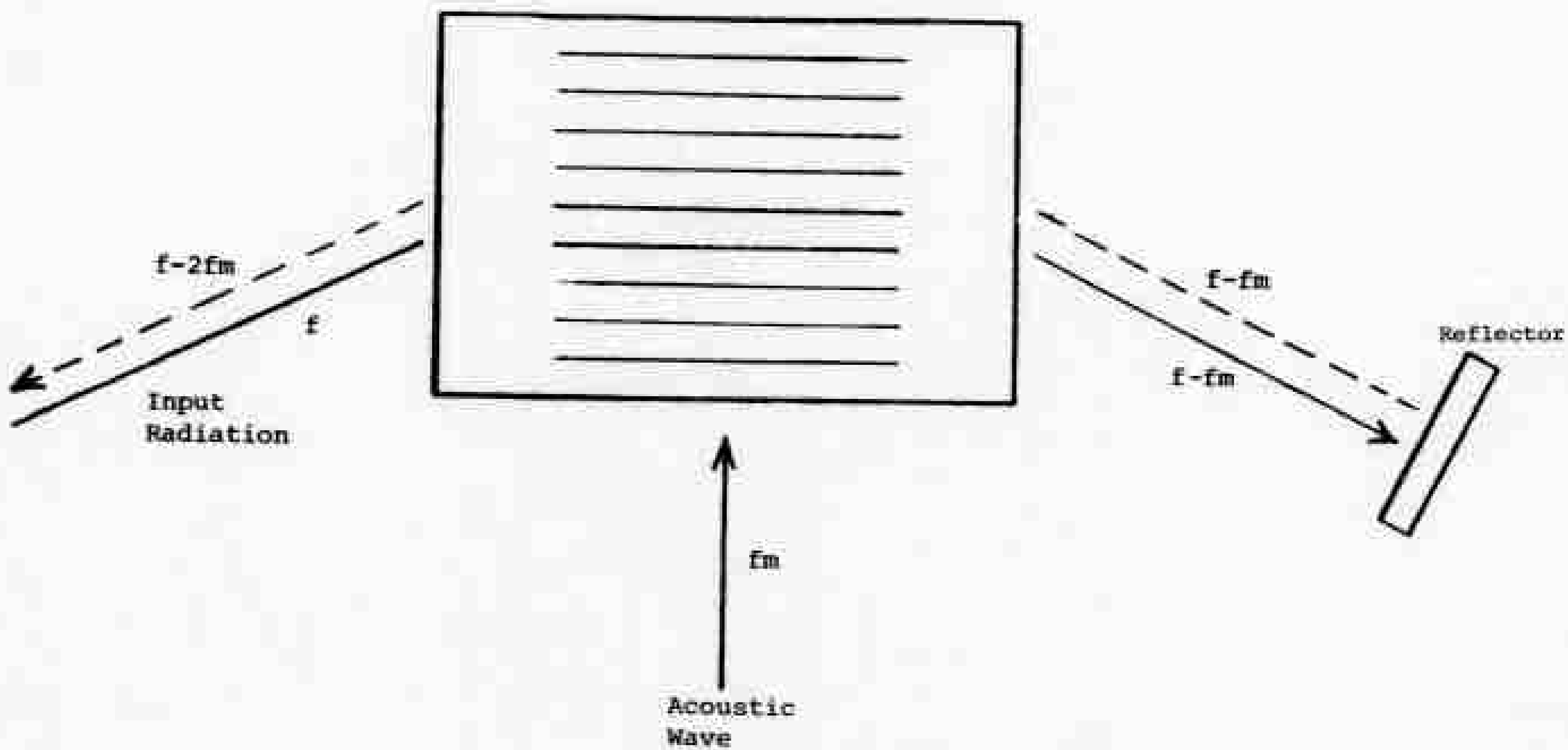

FIGURE 2.0 - 1a Illustration of the Acousto-optic Isolator Concept

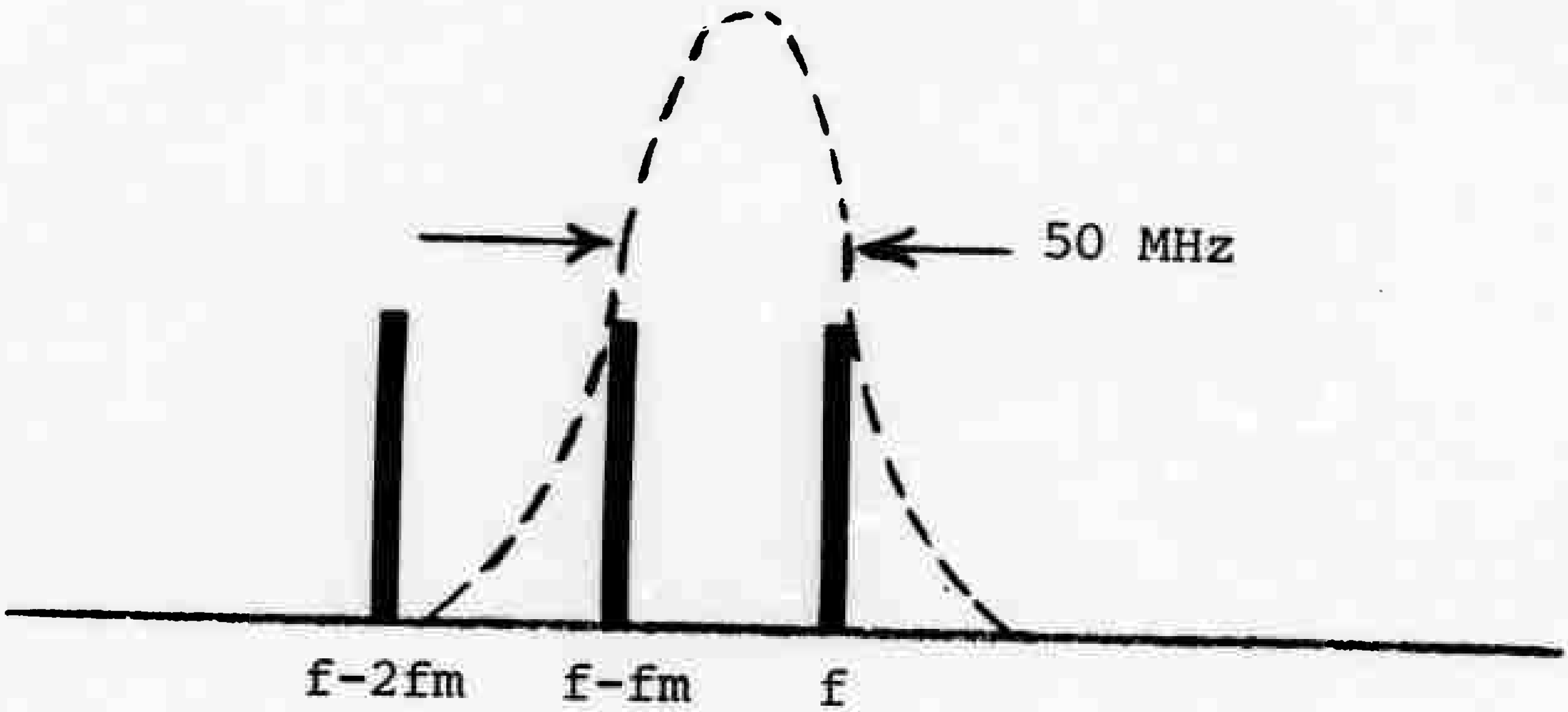

FIGURE 2.0 · 1b Illustration of Reflected Laser Frequency Being Shifted Outside of the Fluorescent Spectrum of the Laser Transition

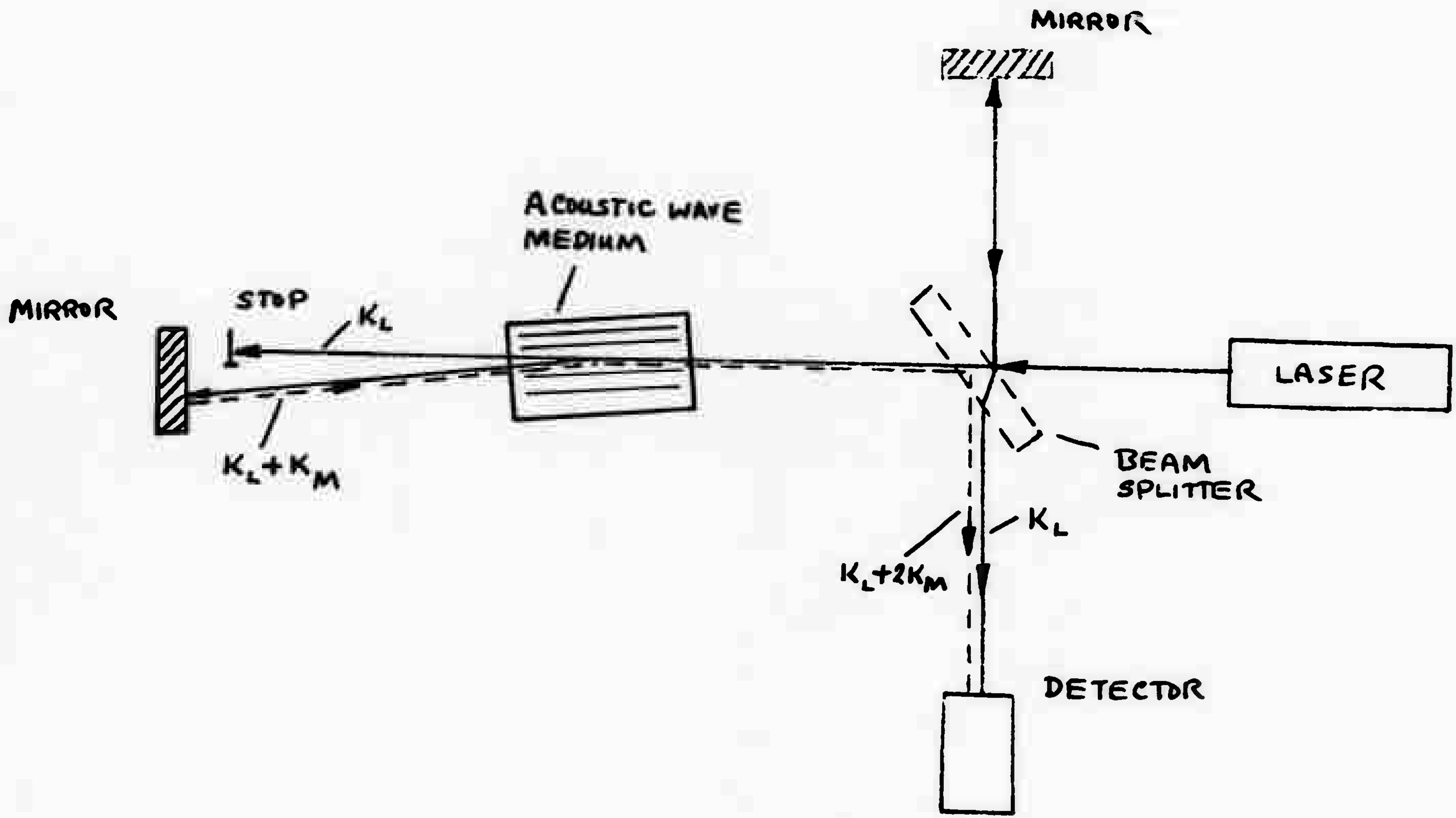

FIGURE 2.0 - 2 Diagram of the Experiment to Verify the Double Laser Frequency Shift Produced by Passing the Laser Bean Through the Acousto-optic Medium Twice

the modulator is removed the 52 MHz signal disappears, but the 26 MHz RFI remains, as indicated in Figure 2.0-3b.

FIGURE 2.0 - 3a Spectrum Analyzer Trace Showing 26 MHz RFI and 52 MHz Beat Frequency Signal Produced by Mixing the Laser Beam with a Beam Which has Traversed the Acoustooptic Medium Twice

FIGURE 2.0 - 3b Spectrum Analyzer Trace Showing Only 26 MHz RFI When Optical Signal is not Reflected Back Through Modulator, Thus Showing That 52 MHz Signal in a) is Caused by Optical Mixing

3.0 EXPERIMENTAL RESULTS

3.1 Device Design and construction

The first phase of this program has been concerned with the construction of the acousto-optic devices. A number of devices have been constructed and tested. The acousto-optic material chosen for all the devices constructed has been single crystal germanium oriented with the faces of the crystal normal to the (111), (112), and (110) axes (Figure 3.1-1). Efficient operation of this material as an acousto-optic medium when a longitudinal acoustical wave is launched along the (111) axis and the laser beam is propagated along the (112) axis has been demonstrated (References 1 and 2). We have also experimentally verified the greater efficiency possible when the polarization of the laser is parallel to the acoustic beam direction rather than being perpendicular to the acoustic beam. We observed at least a factor of 10 difference in the efficiency in these two cases.

The first device used a .5 x .5 x 1 inch germanium crystal with the .5 x .5 inch face normal to the (111) axis. A device of this dimension can be operated in the Deby-Sears region at low frequencies (~20 MHz) and in the Bragg region at higher frequencies (~75 MHz). At intermediate frequencies both effects can be observed.

A Gulton Industries transducer HST-41 cut for 10 MHz was used. This material is prepoled and coated on both sides with conducting silver paint. The device was cut with a wire saw to approximately the size of the .5 x .5 inch face, and leads were bonded to it with silver paint. A transducer was then bonded to each (111) face of the germanium with phenylsalicylate. Two transducers were used so that the propagation of the acoustical wave could be detected.

The bonding process is accomplished by coating both the transducer face and the germanium with liquefied phenysalicylate. The materials are pressed together with a preheated vise. The vise is placed on a hot plate which is allowed to

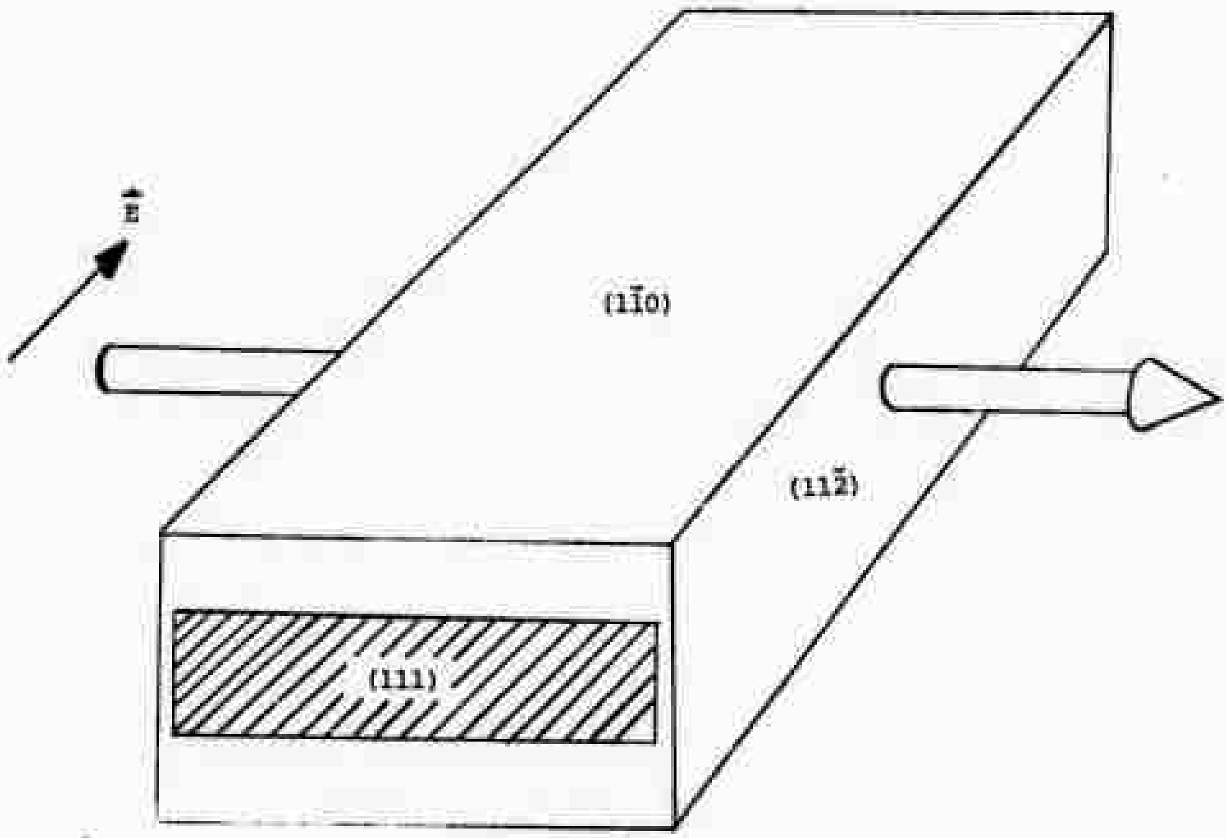

FIGURE 3.1 - 1 Configuration for Efficient Acousto-Optic Modulation in Germanium

gradually cool. When the hot plate reaches a temperature where a sample of phenysalicylate recrystallizes, the crystalline phenylsalicylate is touched to the liquid between the transducer and the germanium thereby causing the entire bond to crystallize.

The device was set in an aluminum mount to which an RF connector was attached. One lead from the transducer was connected to the RF center conductor and the other lead was grounded.

The transducer was first tested with an RF oscillator and amplifier to determine the coupling efficiency of the transducers. The setup for the experiment is shown in Figure 3.1-2. The results are shown in Figure 3.1-2b.

The next step was to examine whether the acousto-optic effect was occurring. The device was irradiated with a CO_2 laser as shown in Figure 3.1-3a. The output from the device was chopped at 200 Hz and focused onto a mercury cadmium telluride detector. The RF energy was then applied to the device. The RF signal was chopped electronically so that a detector could be used to envelope detect the modulated portion of the laser beam. First the detector was used to observe the mechanically chopped laser beam, then it was translated to the theoretical position of the modulated portion of the beam. The modulated beam was found in this position within experimental error. The results shown in Figure 3.1-3b indicate that the beam was deflected. In order to verify that the effect also produced a frequency shift, the output from the detector was connected to a HP 8552A/8553L spectrum analyzer. The results are shown in Figure 3.1-4 for 10 MHz and 30 MHz which is an odd harmonic of 10 MHz. With the CO_2 laser beam incident normal to the crystal face, both the sum and difference frequency could be observed as expected. When the crystal was rotated one side band could be enhanced and the other decreased in amplitude corresponding to operation close to the Bragg regime. Heating of the

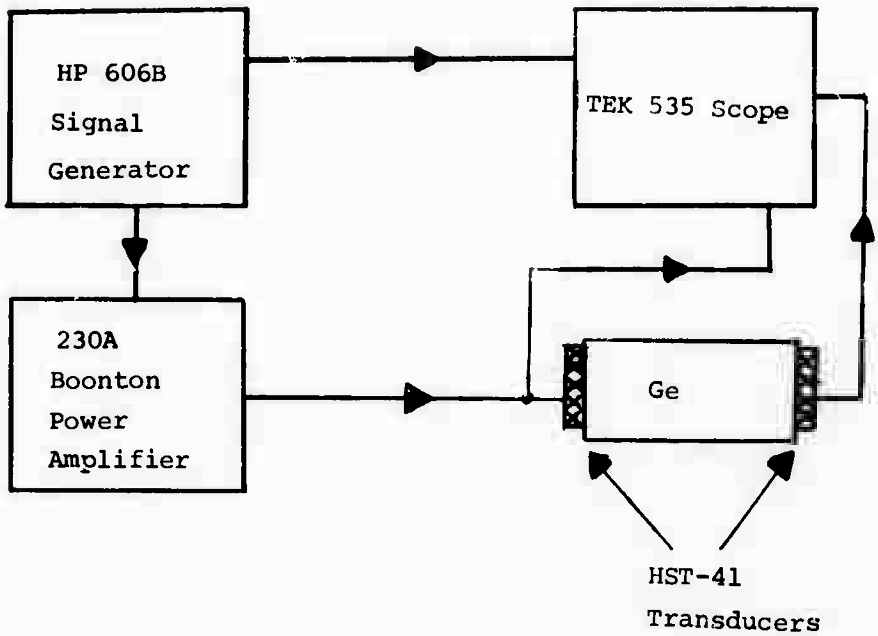

FIGURE 3.1 - 2a   Test Setup for Determining Coupling Efficiency

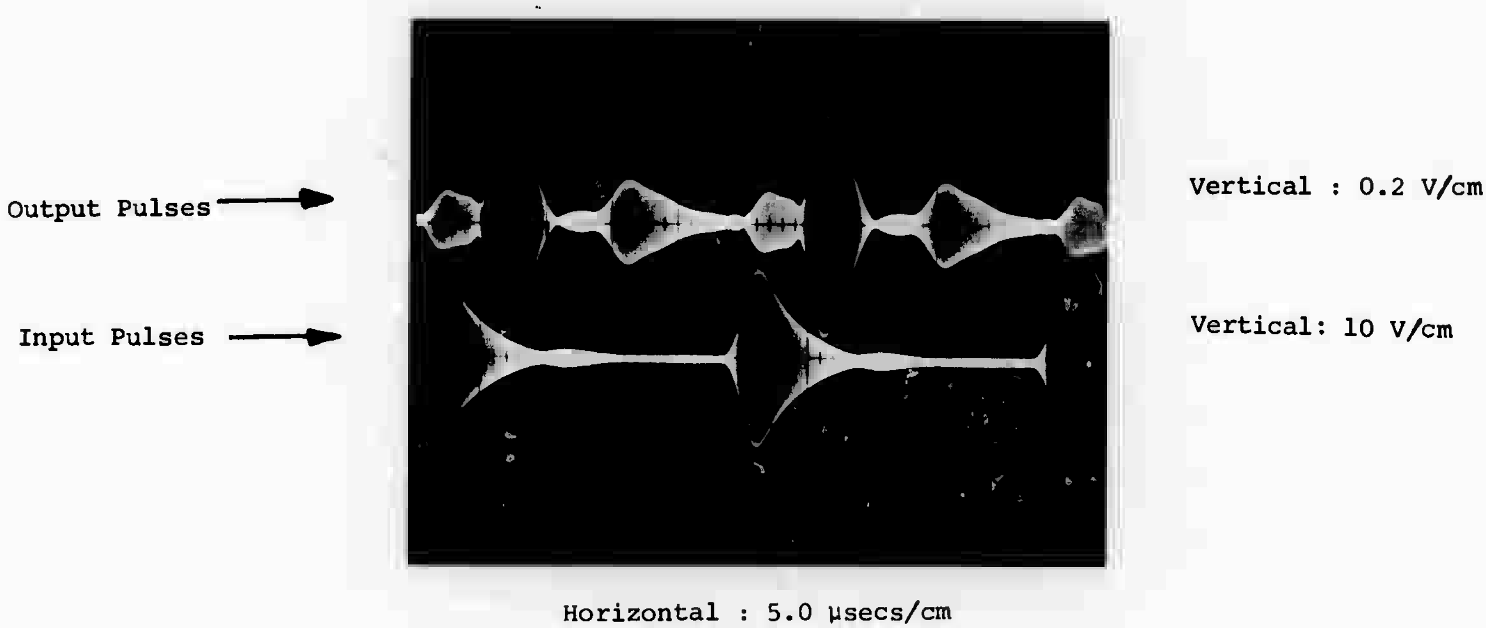

FIGURE 3.1 - 2b   Acoustical Delay and Transmission in the Acousto-optic Device

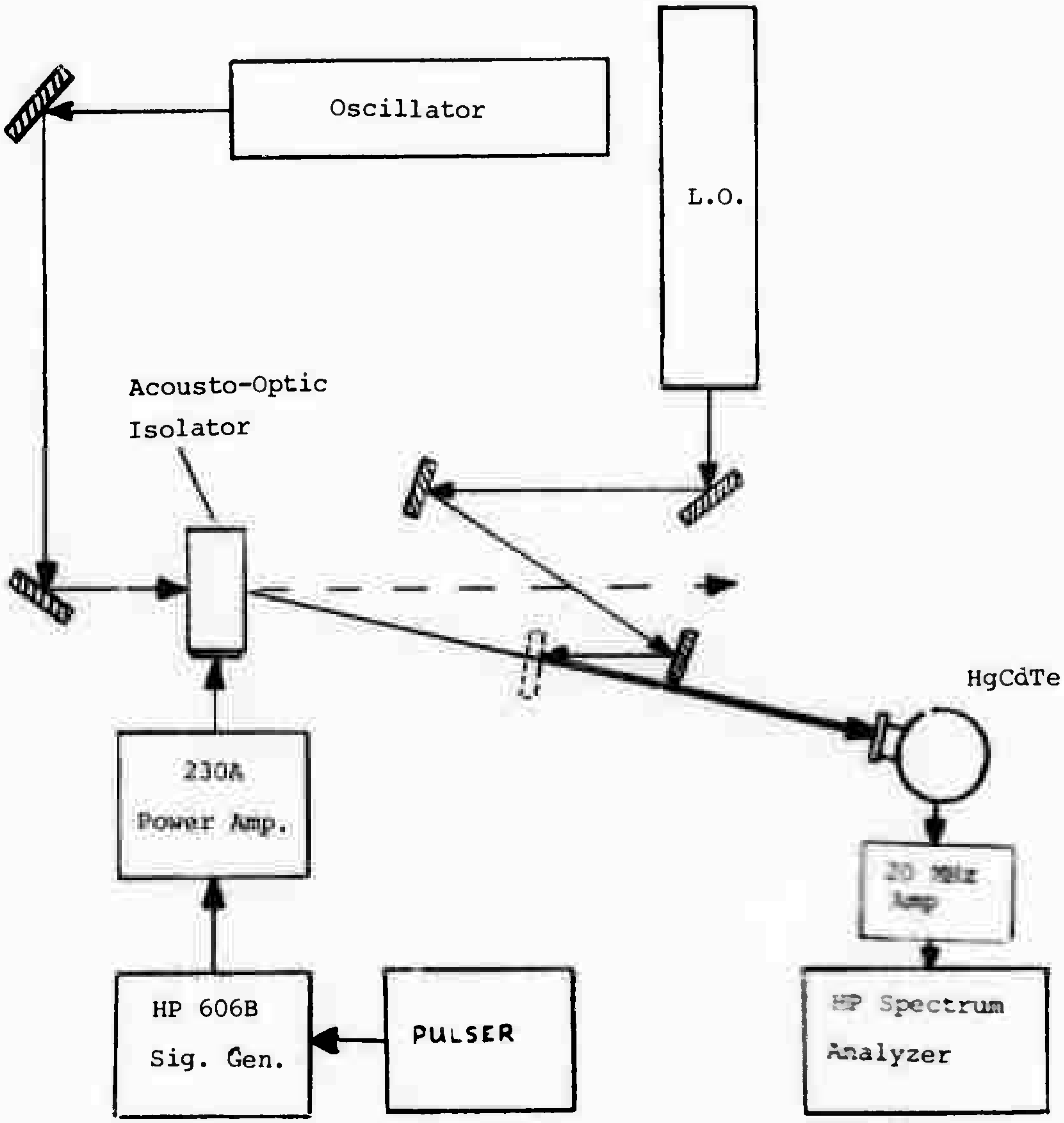

FIGURE 3.1 - 3a Test Setup to Observe Spatial Deflection and Frequency Shift of Modulated Beam

100 mv/cm

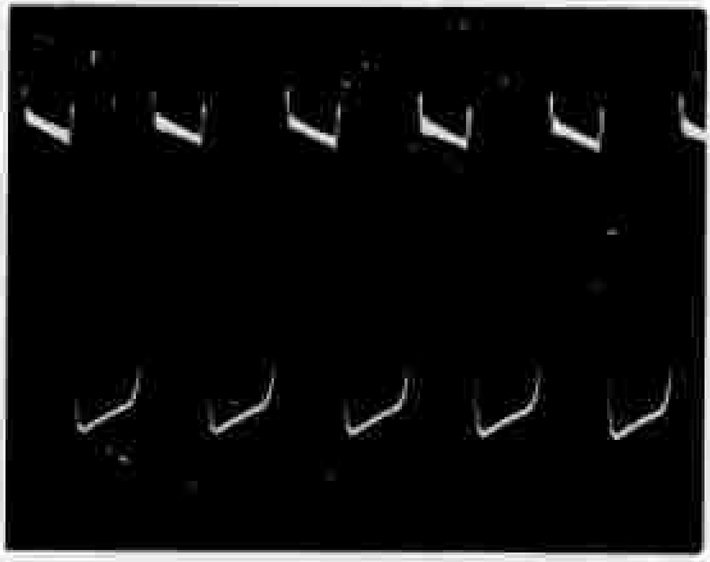

FIGURE 3.1 - 3b
Unmodulated Chopped Laser Beam

2 mv/cm

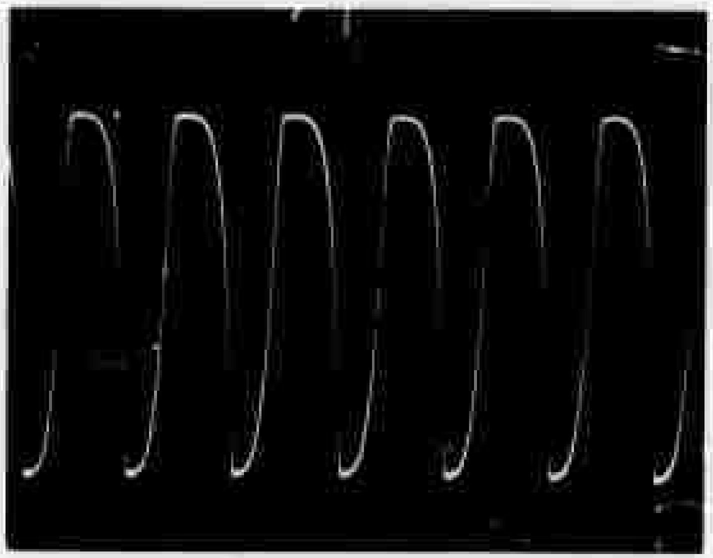

FIGURE 3.1 - 3c
Acousto-optically Modulated
Portion of the Laser Beam

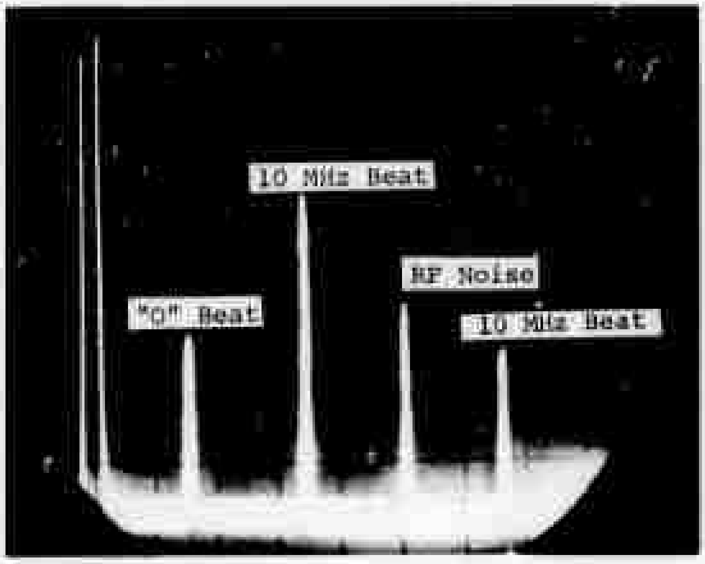

FIGURE 3.1 - 4a 10 MHz Modulated Beat Compared to "0" Beat

FIGURE 3.1 - 4b 30 MHz Modulated Beat Compared to "0" Beat

germanium was observed in these experiments. When the RF power was increased above a certain level the phenysalicylate melted and the efficiency of the interaction decreased. Eventually, the transducer fell off.

Three devices were constructed and tested in the manner described above, and all produced essentially the same results. A device was constructed with a hole connection on the aluminum block so that the germanium could be cooled with gaseous nitrogen. This slight cooling reduced heating effects slightly, thus indicating the efficacy of cooling the device.

An epoxy bond was used next. The principal advantage of an epoxy bond over phenysalicylate is resistance to effects from heating. The epoxy does not melt.

A device was constructed with an epoxy bond. The mixture consists of 5 parts Shell Epon Resin 828 Epoxy and 1 part Shell Epon Curing Agent Z. The device which again is held in a vise is allowed to cure for 12 hours at 100° F. The material can be cured faster but heating to the required higher temperatures can affect the transducer.

When this device was tested it showed all of the properties of the previous devices except that it could be run at higher RF power levels without deleterious effects on the bond as expected.

Three other transducers are in various stages of construction. One is a device using a .5 inch cube of germanium. A second will use water cooling. A third will use a crystal with a .5 x 1.5 inch transducer face so that it can be operated in the Bragg region. A fourth will use a metal wedge at the end of the crystal to reduce acoustical reflections. A fifth will have a fused silica block attached to the germanium so that a helium neon laser beam can be observed with the CO_2 beam.

Several transducer configurations will be used on the modulators being constructed. The various configurations will attempt to optimize the RF energy

coupling into the transducer and take advantage of theoretical considerations such as having a large ratio of acoustical beam width to length.

Additional devices will be constructed using a lithium niobate transducer which has certain high frequency advantages over ceramic materials. The smaller grain structure in lithium niobate makes fundamental mode operation easier to achieve at frequencies of 30 MHz and above. Ceramic transducers, however, can compensate for third harmonic operation with a larger electrical to acoustical transfer.

3.0 EXPERIMENTAL RESULTS

3.2 MOPA Simulator

An experiment was assembled to simulate the MOPA in the radar tracker at RADC. That device has a stable oscillator and 64 meters of amplification in glass sections. The simulator is shown in Figure 3.2-1. A CO_2 laser oscillator and amplifier are used. A diagram of the amplifier is shown in Figure 3.2-2. Radiation from the oscillator passes through the amplifier and can be reflected back into the amplifier by a mirror to simulate high power feedback. Another CO_2 laser is used as a local oscillator to probe the feedback effect. A mercury cadmium telluride detector converts the beat between the local oscillator and the signal to be examined to an electrical signal that can be observed on an oscilloscope or spectrum analyzer. The experiment rests on a sheet of aluminum which is isolated from the table with wheelbarrow inner tubes. The lasers are also isolated from the aluminum by inner tubes.

The CO_2 lasers are flowing gas system each using a grating for the end reflector. These devices can be operated on many lines on either P or R branches of the two possible transition bands. These devices can be tuned to a given line, operated all day, turned off and the next day the laser will begin operating again on the same line. The stability of these devices is indicated by the beat between these devices shown in Figure 3.2-3.

An experiment was performed to insure that the feedback would affect the master oscillator. Radiation from the grating was fed back through the front mirror and a change in the amplitude of the beat frequency signal was observed as illustrated in Figure 3.2-4. This result is shown in Figure 3.2-5. The beat frequency signal increases with the feedback due to constructive interference. If the path is changed slightly, destructive interference results in a decrease

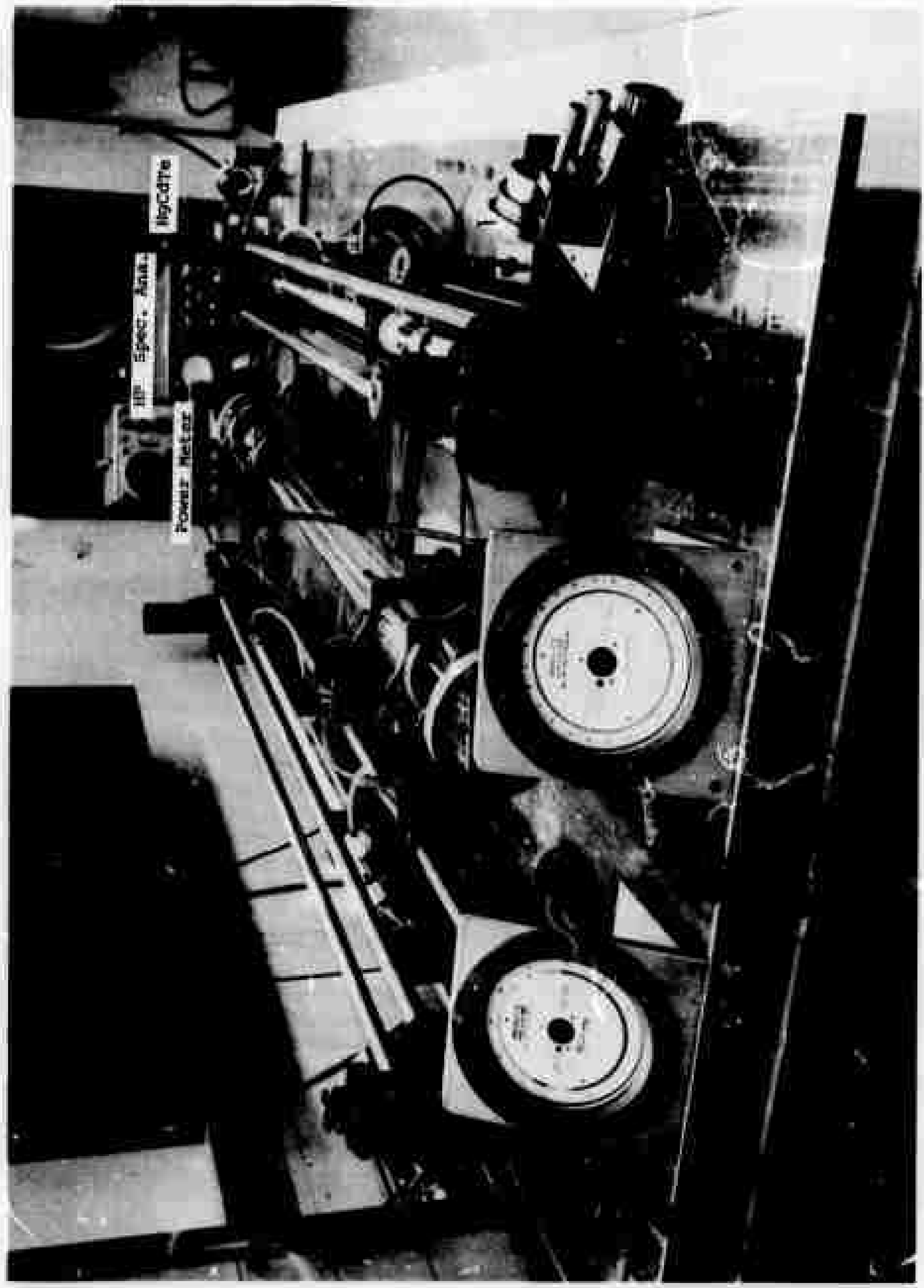

FIGURE 3.2 - 1 Experimental Setup of MOPA Simulator

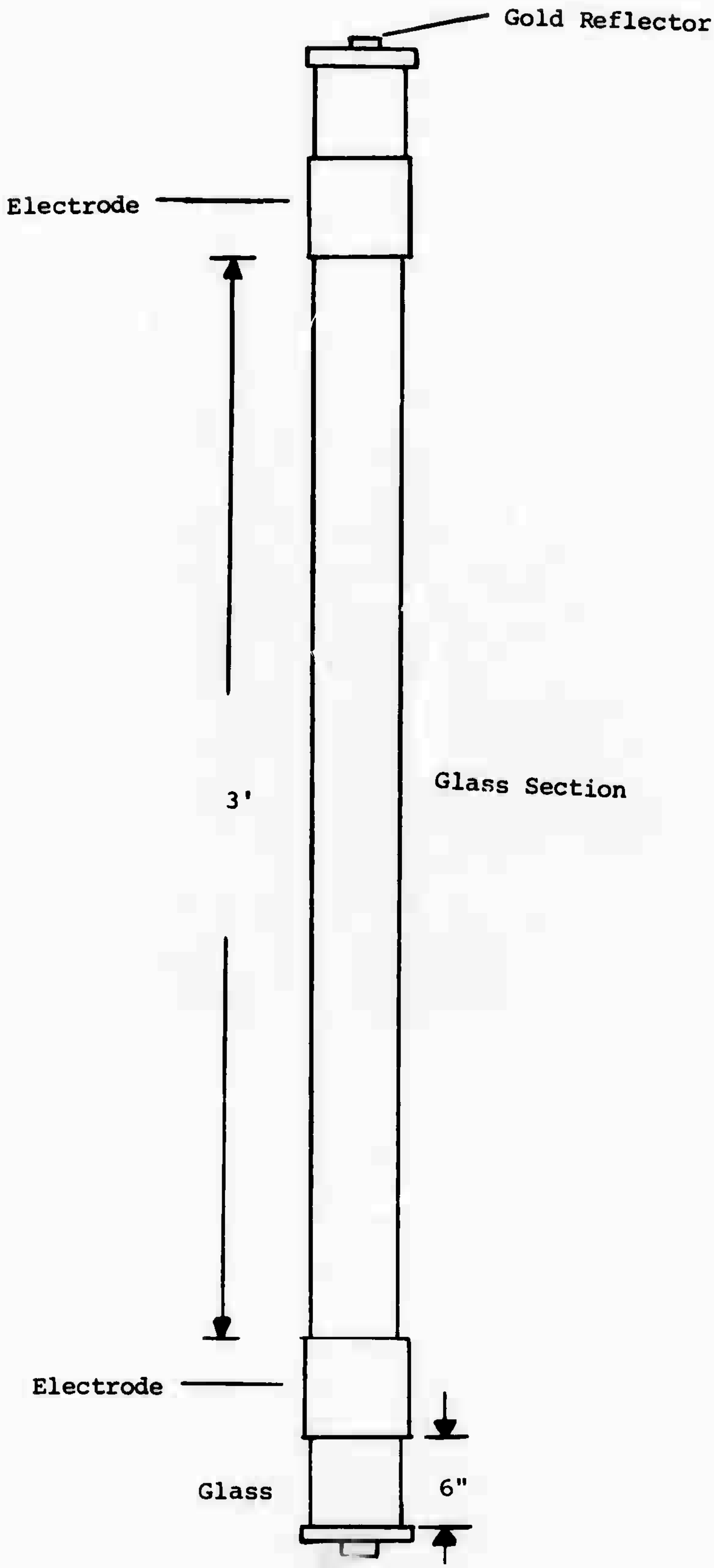

FIGURE 3.2 - 2 Diagram of Amplifier Cell for Feedback Investigation

in the amplitude of the beat frequency signal. The next step in this series of experiments is to translate the feedback signal in frequency and observe the effect.

.5 MHz/cm

FIGURE 3.2 - 3 Spectrum Analyzer Trace Showing Laser Stability - Bandwidth 100 KHz, Sweep Time 2 ms/Div

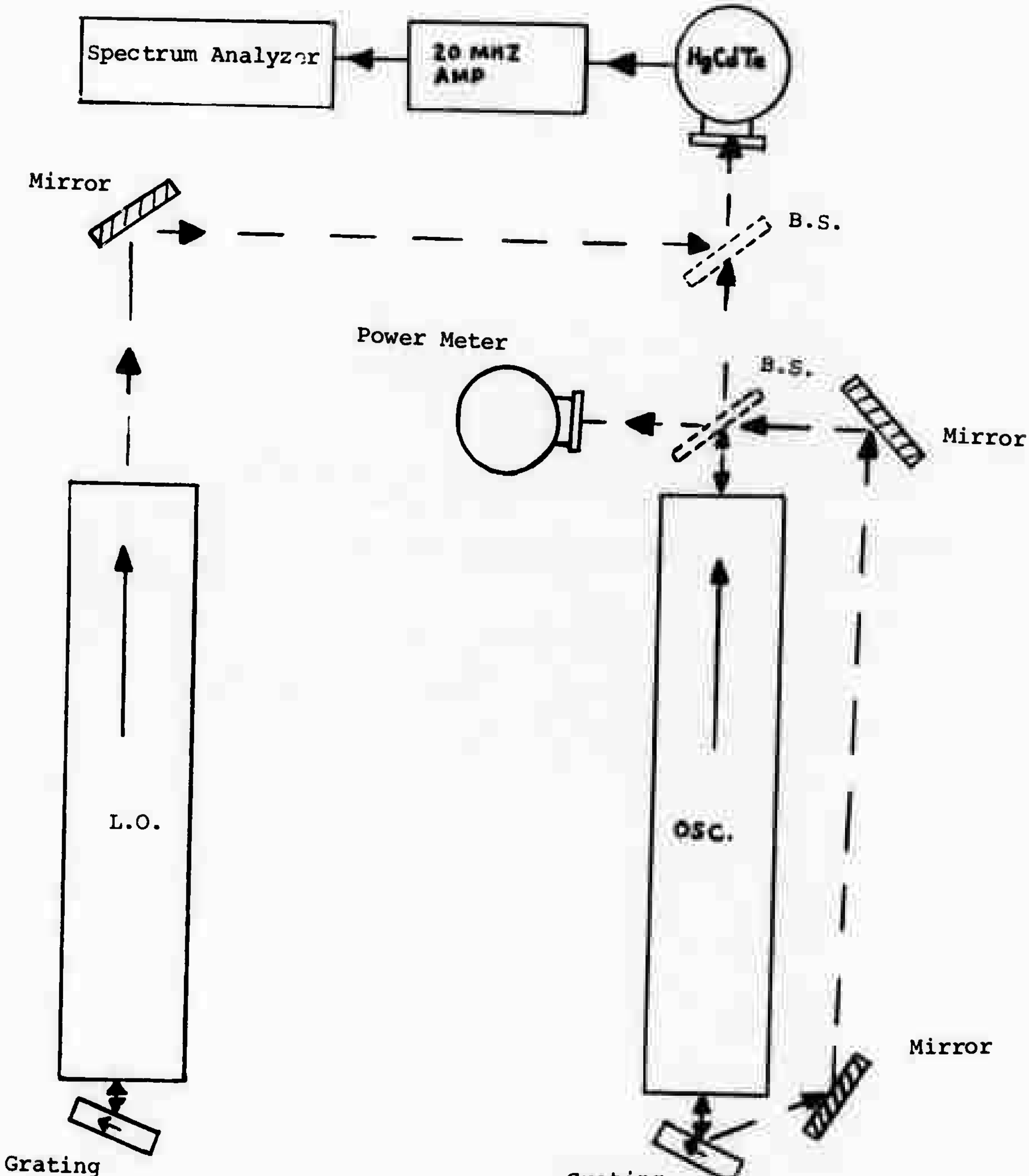

FIGURE 3.2 - 4 Experimental Setup for Feedback into Master Oscillator

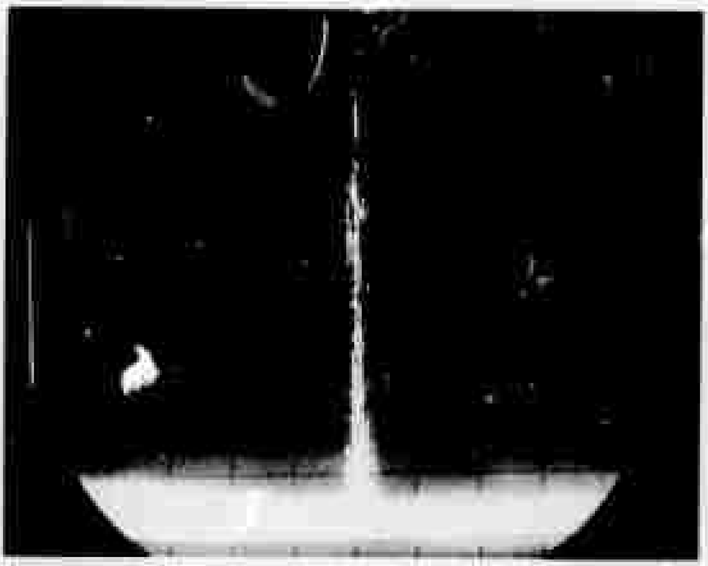

FIGURE 3.2 - 5a Spectrum Analyzer Trace Showing Effects of Feedback Into Oscillator

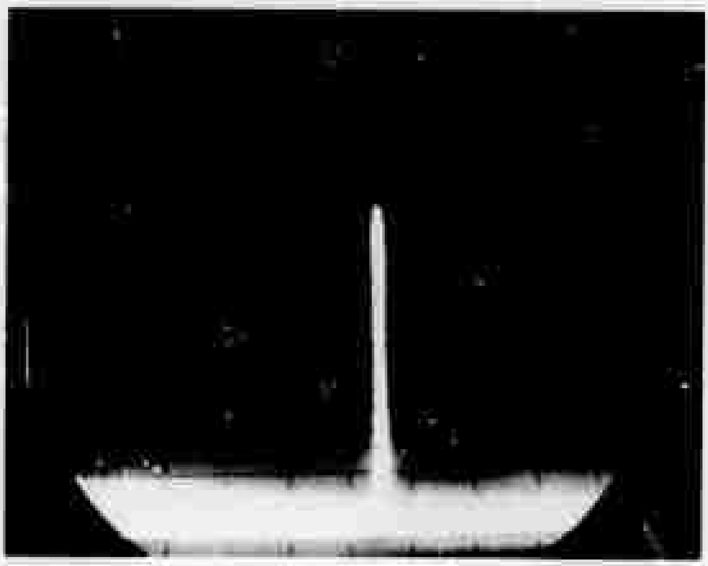

Figure 3.2 - 5b Spectrum Analyzer Trace of Beat Without Feedback

3.0 EXPERIMENTAL RESULTS

3.3 THERMAL AND VIBRATION EFFECTS

We have observed experimentally that acoustic heating of the germanium modulator medium can cause ray bending. This effect was observed using an RF amplifier capable of putting several watts of RF power into the transducer.

A germanium crystal 1.0 x 0.5 x 0.5 inches was mounted in a dry nitrogen cooled holder. Two longitudinal mode transducers were bonded to (111) faces using the epoxy Shell Oil Company number 828 and curing agent Z. Single leads were attached to the transducers using microcircuit silver paint. A CW CO_2 laser beam was then passed through the crystal in the $(11\bar{2})$ direction and polarized in the (110) direction. The laser beam power was about one watt. The laser beam was allowed to irradiate the crystal over several hours with no noticeable heating as would be expected from the low absorption coefficient of germanium in the 2-20 micron range, approximately .032 cm^{-1}.[1] A 30 MHz acoustic wave was then propagated through the crystal by applying an RF voltage to one of the transducers. A rapid rise in the crystal temperature occurred within seconds when no dry nitrogen cooling was used. When dry nitrogen was blown across the crystal a stable operating temperature was reached in about one minute after the RF signal was applied.

The laser beam was observed on a HgCdTe detector after it had passed through the germanium. To observe the power in the beam a 200 Hz chopper was placed in the beam at a point after it had passed through the germanium modulator. With the RF signal applied to the modulator the chopped signal was observed to diminish slowly.

The detector was translated to determine if this was an acousto-optic effect. Measurement of the beam shape at the detector in Figure 3.3-1, shows that most of the laser beam was slightly shifted. The shift was measured to be 6.2 milliradians. Heterodyning of the shifted beam with an unmodulated beam showed that the beam had not been frequency shifted. This was expected since at 30 MHz an acousto-optically shifted beam would have been spatially shifted about four degrees. The germanium was also translated across the laser beam to observe the effect as the laser beam was moved further from the input transducer. The separation was found to reduce. With the beam set 3.0 millimeters from the input transducer the thermal deflection was 10 milliradians. At the center of the crystal the deflection was 6.2 milliradians and with the beam 3.0 millimeters from the opposite end the deflection had reduced to 2.7 milliradians.

This slight shift is a thermal effect associated with changes in the local index of refraction of the germanium. As the plot in Figure 3.3-1 shows there was no noticeable increase in absorption observed at the elevated temperature although germanium is known to have a rapid increase in absorption at temperatures above 300°K due to free carrier absorption.[1] Even though the germanium was heat sinked to the aluminum holder with a mechanical clamp, its temperature with an applied RF signal was perhaps 50 to 100° C above room temperature.

Thus as the measurements across the germanium show an index gradient is produced by the heat generated at the input transducer. As a light beam passes into the germanium crystal it is refracted in the direction of decreasing index or toward the input transducer. This was observed experimentally. Both transducers were used as inputs for the RF signal while

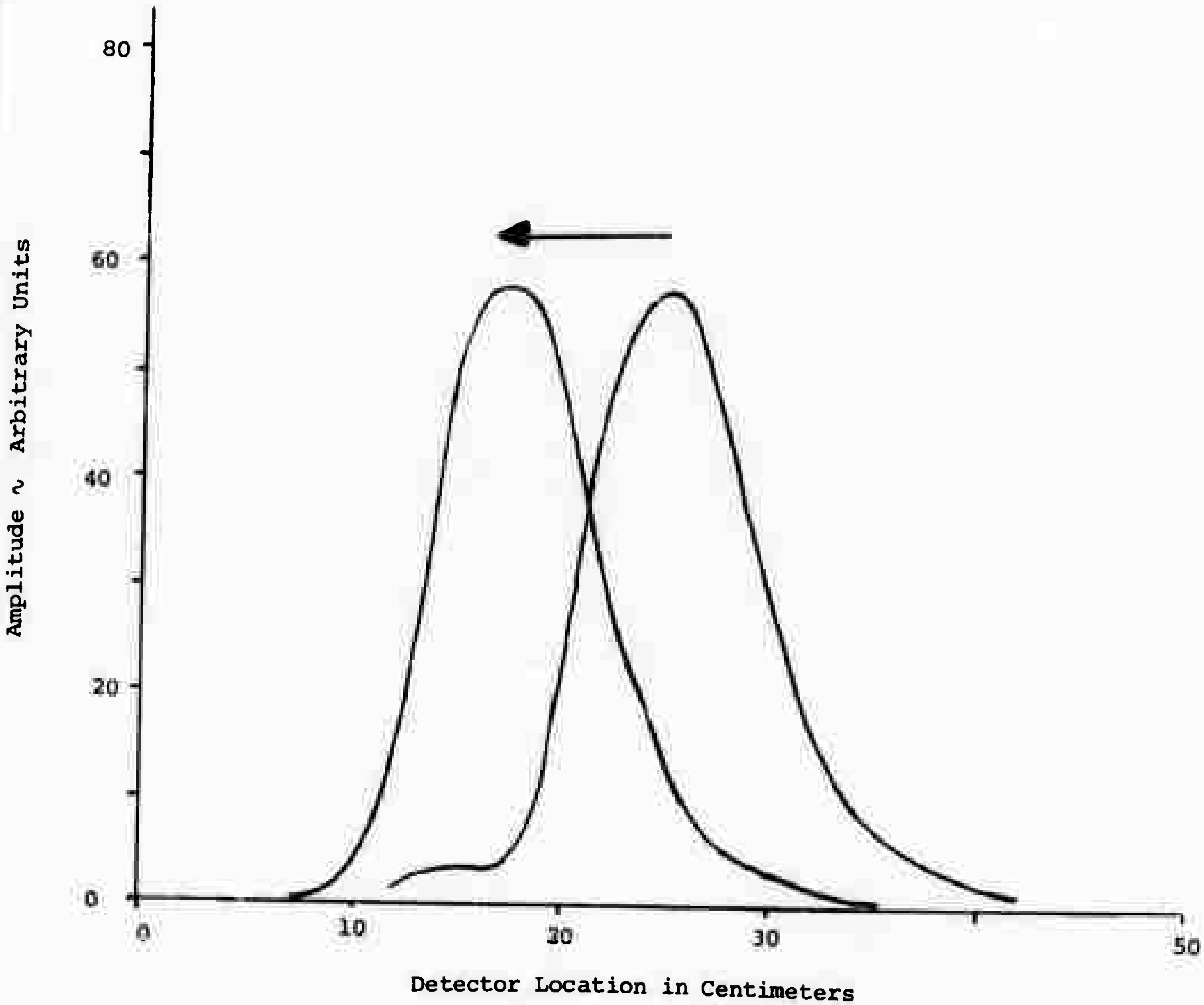

FIGURE 3.3 - 1   Observation of Thermal Deflection

the crystal was held in place. In both cases where the RF signal was applied the laser beam was bent in the direction of the input transducer. While each transducer was being used as the input the crystal was slowly rotated up to a 45° angle to the beam normal in the two horizontal directions. Only a small change of less than five percent was observed in the deflected beam over the angle of rotation. For the transducer configuration used at 30 MHz the acousto-optic modulation is in the Bragg region. The degree of modulation is very sensitive to the angle of orientation of the crystal to the laser beam axis in the Bragg region. The small amplitude variations in the thermally deflected beam with large angular rotation is further evidence that it was not an acousto-optic modulation but was a separate effect. Figure 3.3-2 gives a simple diagram of bending by an index gradient.

The thermal bending of the laser beam is an undesirable effect and methods for reducing it are being investigated. Initially it was discovered that when the input frequency of the RF signal was not tuned to a resonance of the transducer the acousto-optic modulation was not observable. This would indicate that the RF power being put into the transducer is probably being converted to heat rather than to an acoustic wave in the germanium. Further, it was observed that even with the thermally induced index gradients across the crystal that the amplitude of the acousto-optically modulated beam changed only slightly as the laser beam was translated across the crystal face.

Vibrational effects were observed on the output of a CO_2 laser with feedback. The setup in Figure 3.3-3 was used. The lasers are tunable with a grating used as one end of their cavities. Radiation reflected off the grating escapes from the side of the cavity as shown. To demonstrate the effects of feedback this output was returned to the cavity using two mirrors and a beam splitter as shown.

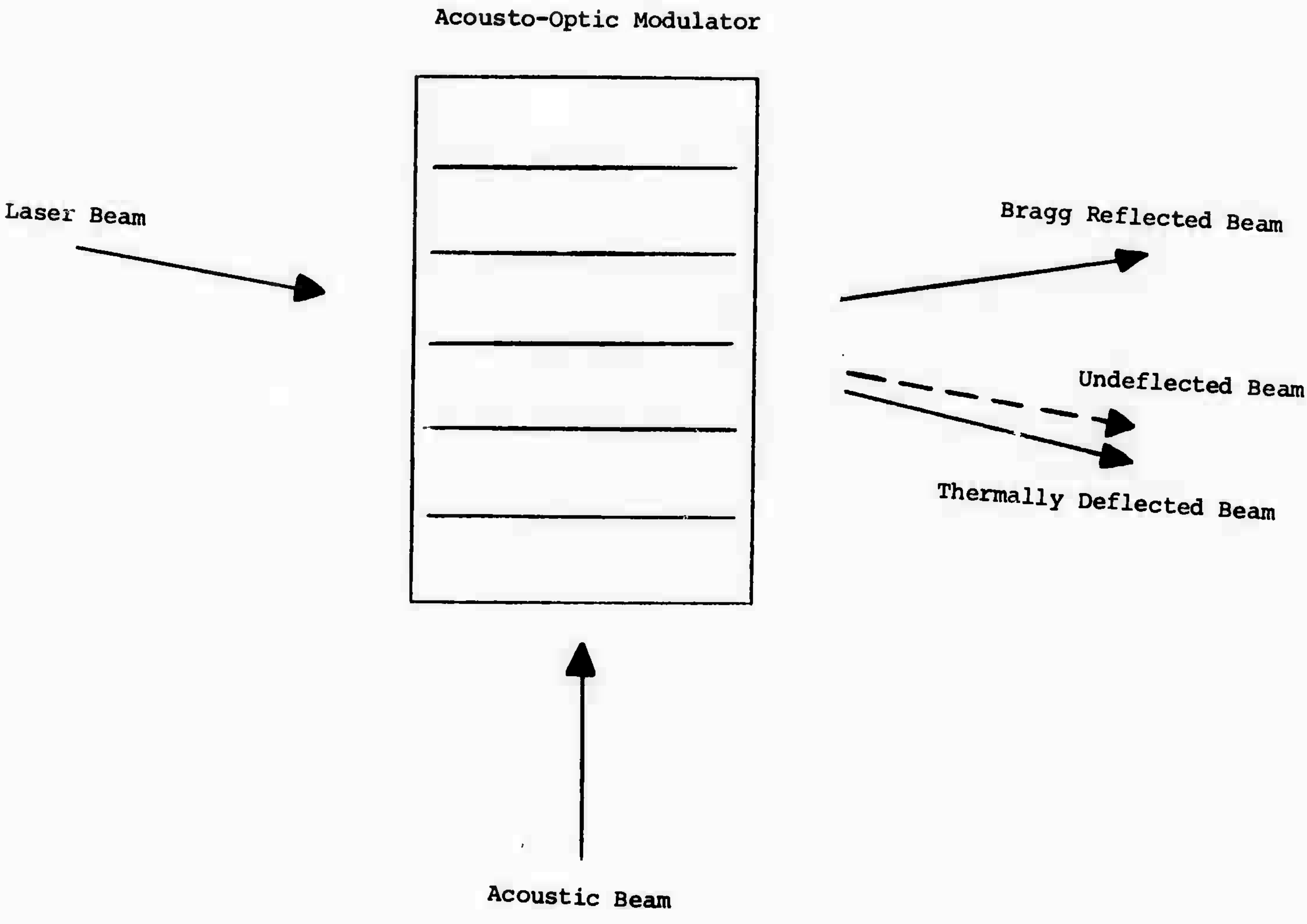

FIGURE 3.3 - 2 Diagram of Deflection Due to Thermally Induced Index Gradient

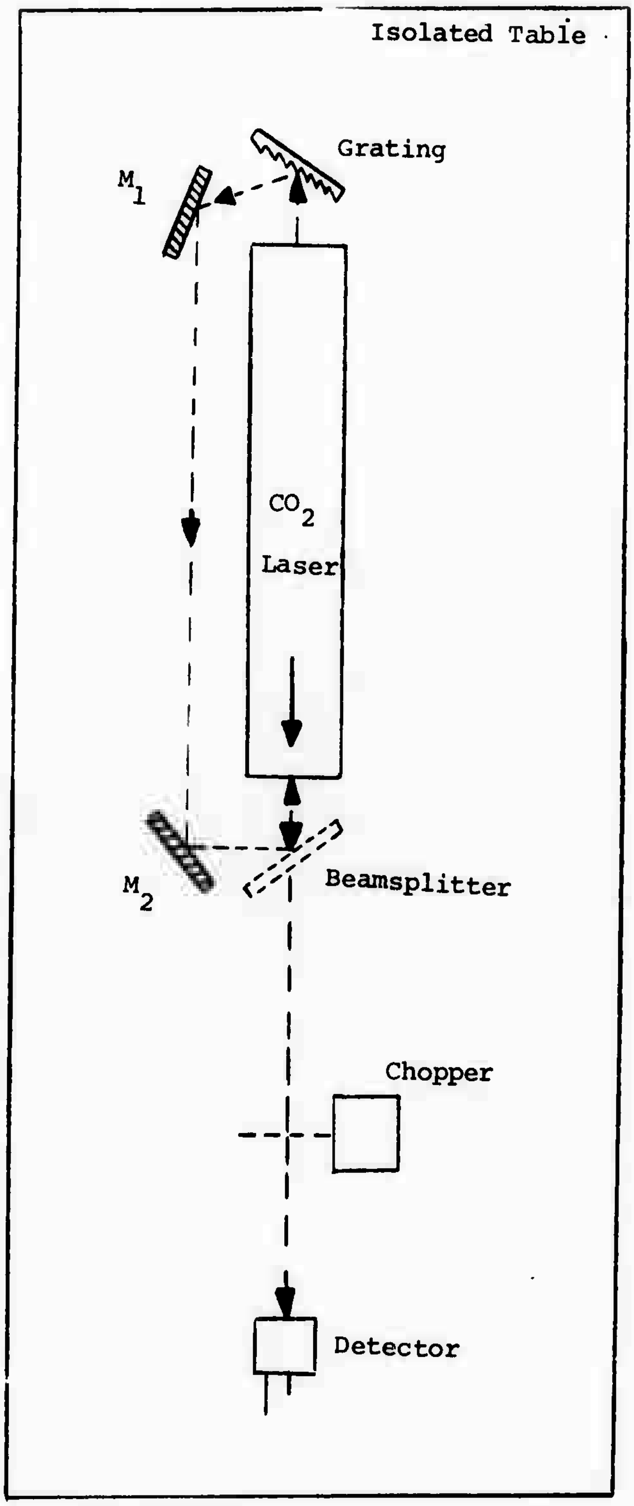

FIGURE 3.3 - 3 Experimental Setup to Determine Effects of Vibrations on Laser with Feedback

Without the mirror M_2 in place the laser cavity was vibrated with a sharp tap on its casing. The photo on the top in Figure 3.3-4 shows the effect on the envelope detected output. The photo was taken following the tap. The horizontal sweep is 10 milliseconds / centimeter. With the mirror M_2 in place to produce feedback the laser cavity was again vibrated with a sharp tap. The effect on the envelope detected output in this case is shown in the bottom photo in Figure 3.3-4. Comparison of the photos indicates that in the feedback condition the laser output is more sensitive to vibration induced noise. The effect of the acousto-optic isolator on this condition will be investigated. The more isolation that the isolator can produce should proportionately decrease this condition.

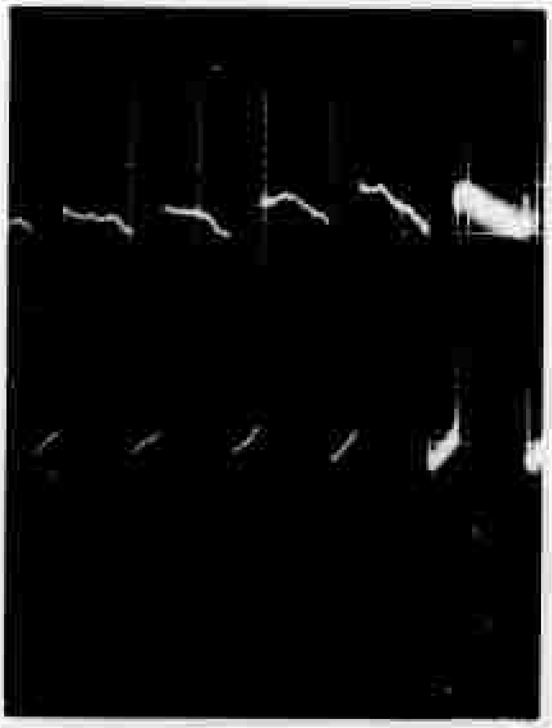

FIGURE 3.3 - 4a Signal Without Feedback

FIGURE 3.3 - 4b Signal with Feedback

FIGURE 3.3 - 4 Scope Trace Showing Effects of Vibration due to Feedback

4.0 FUTURE PLANS

During the second half of this contract a number of experiments must be performed. These include injection locking feedback from the amplifier to the oscillator in the simulator and making tests on an isolator device. These tests include the effect of the isolator on the locking as a function of acoustical power input, frequency input, angle between laser beam and transducer, laser power, beam size and feedback level. Also to be measured are the RF, acoustical, and insertion losses of the device. Thermal and vibration effects on the isolator will also be investigated. Finally, an optimized breadboard based on the information gathered will be constructed and tested.

The work that has been performed thus far on the contract has led to some results that were partially anticipated, but nevertheless, have introduced avenues of investigation that are beyond the scope of the current contract. The thermal effects that have occurred for example are such that further investigation and solutions are warranted. Also, the current contract is concerned with studying the concept. If the efficiency of the concept is shown, then work should be performed on the electrical portion, the housing and other parts to achieve a prototype model.

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